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Self-Smoothing of Laser Light in Plasmas

H.A. Baldis, W. Rozmus, C. Labaune, B. Cohen and R. Berger

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The modification of the optical characteristics of a laser beam by a plasma is a key issue in laser–plasma coupling. It is critical to understand how this takes place, if we are ever to understand the interaction processes in the plasma corona as well as the coupling at super-high intensities—as when laser pulses approach Petawatt intensities. Interpreting and understanding parametric instabilities in laser-produced plasmas has been a problem of increasing complexity. Improvements in diagnostic capabilities in experimental studies, as well as refinements in the modeling (using different numerical techniques), are showing a complex scenario: strong interplay among instabilities, modification of the plasma conditions caused by the instabilities, and modification to the initial distribution of laser intensity inside the plasma. Of particular interest are stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS), instabilities which have been studied extensively during the past 20 years, both theoretically and experimentally. Until now, most studies—mainly driven by requirements associated with inertial confinement fusion (ICF)—have concentrated on backscattering instabilities. The role of forward instabilities has not received much attention, despite having the potentials for strongly modifying the overall laser–plasma interaction region.

The objective of this project is to study numerically the nonlinear enhancement of large-angle, forward scattering of two identical laser beams propagating in a preformed plasma. It is known that filamentation instability and self-focusing are capable of modifying laser-beam geometry, altering the electromagnetic-field distribution and spectral properties. These instabilities, combined with forward SBS, apparently cause a plasma-induced smoothing (self-smoothing) of the laser light as it propagates through the plasma. The final effect may have consequences similar to the temporal smoothing introduced intentionally in many laser systems. We do not propose this phenomenon as a smoothing technique; however, we claim that the understanding of this effect is crucial to the interpretation of experimental results on parametric instabilities.

Results of different experiments with underdense targets have shown dramatic changes in the transmitted light propagation characteristics and spectral properties. The nonlinear enhancement of large angle forward scattering of two identical laser beams propagating in a preformed plasma has been observed experimentally. The spectral analysis of the forward scattered light shows two components, one which is unshifted with respect to the initial laser light frequency, and the other which is red-shifted. The red-shifted component is found to be strongly enhanced in the case of crossed beam interaction in comparison with that of one beam illumination. Several processes have been identified as contributing mechanisms to these "self-smoothing" effects. They are filamentation, forward stimulated Brillouin scattering and different mechanisms giving rise to non-thermal levels of ion acoustic fluctuations in the plasma. The latter are the least understood. They involve localized heating of the plasma, return current instability due to the heat flow, and direct plasma response to the randomized laser beams.

A progress in understanding of nonlinear propagation of laser beams has been achieved through kinetic simulations on the short spatial and temporal scales. These, primarily particle-in-cell simulations have elucidated a role of ion wave nonlinearities such as ion heating and ion wave coupling in the low frequency plasma.response to the laser beams. A large scale evolution of ion wave response and its effect on the transmitted light has been studies so far using simplified fluid models, which are unable to explain the observed magnitude of the spectral shift, angular distribution of light and its dynamical behavior. A comprehensive effort combining analysis of experimental data from Thomson scattering and spectroscopic measurements with detailed transport models and new theories of the Thomson scattering cross section, is proposed to improve our understanding of background plasma conditions, which as a result of the laser plasma heating include strongly enhanced sound wave levels.

Figure 1 shows the numerical spectra that we obtained during FY1999 from 2-D simulations in which a system of nonparaxial electromagnetic and ion acoustic-wave equations was solved in Cartesian geometry. The two incident beams are symmetric with regard to the *x*-axis. The transmitted light is collected along different angles *q* in the near-field domain and analyzed spectrally. The electron temperature, T_e, and electron density, n_e, used in our numerical simulations were: $T_e = 0.5$ keV, $n_e = 0.3\ n_{cr}$ where n_{cr} is the critical density for the laser light. The simulations were carried out over 300 ps. To account for the laser time-history used in experiments, the laser-beam intensities were ramped in time. Figure 1(a) shows the spectra of the transmitted light as a function of time for the case of a single-beam indication; Fig. 1(b) shows the same, but for the case of the two-beam irradiation geometry, at an angle of 22 degrees.

Our results correspond well to observed features in the experiments (Labaune, C., et al., UCRL-JC-135653). In the simulations, the onset of this red-shifted component can be clearly identified as occurring at the moment when the average intensity of the beam speckles (high intensity regions) reaches the critical value for self-focusing. Thus, at this moment a large number of speckles are unstable with respect to self-focusing and to the subsequent instabilities of a light trapped in a filament. It is important to notice that it is approximately at the same moment that a broad, red-shifted component appears in the single-beam spectra.

The work performed under this project helps to explain features observed in experiments based on the modification of the laser field due to the growth of forward scattering. This is an important step towards our future understanding of parametric instabilities on laser produced plasmas.

Publications

Rozmus, W., et al., "Calculations of thermal transport and enhanced ion-acoustic fluctuations from Thomson scattering measurements in the high-Z laser produced plasmas," UCRL-JC-131460, 99-ERI-018.

Baldis, H. A., C. Labaune, W. Rozmus, A. Maximov, *Forward Scattering as a Potential Self-Smoothing Phenomena,* UCRL-MI-133230, 99-ERI-018.

Labaune, C., et al., "Enhanced forward scattering in the case of two crossed laser beams interacting with a plasma," UCRL-JC-135653, 99-ERI-018.

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UCRL-JC-131460 Abs

Calculations of thermal transport and enhanced ion-acoustic fluctuations from Thomson scattering measurements in the high-Z laser produced plasmas*.

W. Rozmus[1,2], S. Glenzer, K. Estabrook, H. A. Baldis[2],
J. S. DeGroot, B. MacGowan, and P. E. Young[2]
Lawrence Livermore National Laboratory, Livermore, CA 94550

An expression for the Thomson scattering cross-section in inhomogeneous plasmas is derived and applied to experimental results from gold plasmas produced by a beam of the Nova laser. Analysis of simultaneous measurements of Thomson scattered light with the frequency shifts corresponding to ion-acoustic and Langmuir resonances is used to determine electron density, temperature, plasma flow and average ionization state in stable plasmas close to equilibrium. In hot, dense plasmas inhomogeneities of the flow and density increase the width of resonance lines in the scattered light spectra, far beyond broadening due to particle collisions. On the other hand asymmetry in the intensity of ion-acoustic resonances allows for the calculations of a heat flux and a thermal transport coefficient. These calculations have been done for the long scale temperature variations corresponding to the Spitzer-Harm thermal transport and for the large temperature gradient in the nonlocal transport regime. Measurements show also increased levels of ion-acoustic fluctuations due to localized plasma heating by the Thomson probe and the electron return current. This effect has been observed in high-Z plasmas which experience rapid radiation cooling.

[1] *On leave from the Department of Physics, University of Alberta, Edmonton.*
[2] *Institute for Laser Science and Applications (ILSA), LLNL.*
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3rd International Workshop on Laser Plasma Interaction Physics

Forward Scattering as a Potential Self-Smoothing Phenomena

H.A. Baldis, [1] C.L. Labaune, [2]
W. Rozmus, [3] and A. Maximov

[1]*Lawrence Livermore National Laboratory*
P.O. Box 808, L-411
Livermore, CA 94550
[2]*LULI, Ecole Polytechnique, France*
[3]*University of Alberta, Edmonton, Canada*

Abstract:

The modification of the optical characteristics of a laser beam by a plasma is a key issue in laser-plasma coupling. It is crucial to understand ***how*** this takes place, if we are ever to understand the interaction processes in the plasma corona, as well as the coupling at super high intensities like with PW laser pulses.

We have preliminary data that uniquely shows that a) the transfer of laser energy to forward instabilities can be substantial, and b) that the laser beam ***after*** propagation through that plasma, shows a strong near field modification of the laser intensity distribution across the beam.

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Physical Review Letters

URCL-JC-135653

Enhanced forward scattering in the case of two crossed laser beams interacting with a plasma

C. Labaune[1], H. A. Baldis[2], E. Schifano[1], B. S. Bauer[1,*], A. Maximov[3], I. Ourdev[3], W. Rozmus[3,2], and D. Pesme[4]

[1]*Laboratoire pour l'Utilisation des Lasers Intenses, Ecole Polytechnique, CNRS, 91128 Palaiseau cedex, France*

[2]*Institute for Laser Science and Applications, Lawrence Livermore National Laboratory, Livermore, CA 94550, USA*

[3]*Theoretical Physics Institute, Department of Physics, University of Alberta, Edmonton T6G 2J1, Alberta, Canada*

[4]*Centre de Physique Théorique, Ecole Polytechnique, CNRS, 91128 Palaiseau cedex, France*

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Abstract

The nonlinear enhancement of large angle forward scattering of two identical laser beams propagating in a preformed plasma has been observed experimentally. The spectral analysis of the forward scattered light shows two components, one which is unshifted with respect to the initial laser light frequency, and the other which is red-shifted by a few Angstroms. The red-shifted component is found to be strongly enhanced in the case of crossed beam interaction in comparison with that of one beam illumination. Two dimensional numerical simulations show that this enhancement is due to large angle forward stimulated Brillouin scattering in which each beam serves as as seed for the forward scattering of the other.

Typeset using REVTEX

The studies of laser plasma interaction physics in preformed plasmas with crossed beam illumination have two important applications: understanding the potential energy exchange mechanisms between the crossed beams, and providing new insight into the evolution of parametric instabilities under well controlled experimental conditions [1–3].

Energy transfer between crossed-beams could destroy the carefully designed energy balance between the multiple laser beams in the inertial confinement fusion (ICF) experiments, thus affecting the symmetry of a pellet illumination [4]. So far, experiments [5,6] have shown modest energy transfers, in apparent agreement with stationary theory predictions [7]. Kirkwood et al. [5] observed a small energy exchange between two crossed laser beams with different frequencies. The energy transfer was mediated by the resonant ion sound wave (ISW) generated by the optical mixing of the two beams. Wharton et al. [6] obtained similar results to [5] with two equal frequency crossed beams interacting in a flowing plasma. Due to the Doppler shift, the frequency of the ISW generated by the beating of the two beams was zero in the laboratory frame, thus allowing for an energy transfer between the beams via the resonant scattering on this ion sound wave.

In this Letter, we report on the first experimental observations and supporting numerical simulations showing a large angular beam spreading, spectral broadening and red shift of the transmitted light for two equal frequency crossed beams interacting at 22.5°. A broad frequency spectrum and large angular spread of the transmitted light have already been observed in single beam interaction experiments [17,18]. These effects are related to the so-called plasma-induced laser beam smoothing. The latter involves the self-focusing instability of speckles containing more power than the critical power for self-focusing, and the subsequent dynamical evolution of laser filaments, coupled to forward SBS [13]. In the case of single beam experiments, plasma self-induced smoothing gives rise to angular broadening, spectral broadening and red shift of the transmitted light [20,21], which have been clearly observed in experiments [10,17,18] and described in numerical simulations [19,20]. In the case of the crossed beam illumination considered here, plasma self-induced smoothing is found, in addition to these single beam effects, to dramatically enhance the large angle forward SBS by which the energy of one beam can be transferred to the other.

Experiments [10] were carried out on the 6-beam LULI facility at Ecole Polytechnique, using three 0.53 μm beams to preform and heat the plasma from a thin exploded plastic foil, two 1.053 μm beams as interaction beams, and one 0.35 μm beam as a probe beam for Thomson scattering diagnostics. The interaction beams (labeled 1 and 2, respectively, in the present text) had identical characteristics. They were focused with $f/6$ lenses through random phase plates (RPP), producing a focal spot diameter of 320 μm (containing 62% of the total energy), and maximum average intensity of 8×10^{13}W/cm^2. The angle between the two beams was 22.5°. The main diagnostic of these experiments was a spectrometer coupled with a streak camera providing time-resolved spectra of the light collected along the forward direction of beam 1. The light was collected with an $f/4$ lens, off-axis from beam 1 by 3°. The collected signal included the transmitted light contained within the focusing cone of beam 1, and the forward scattering light with scattering angles extending up to 11° from the beam 1 axis. We checked by using masks that most of the light transmitted in the forward direction of beam 1 was collected this way. The spectral and temporal resolutions were 0.5 Å and 20 ps, respectively. Fast photodiodes were used to measure the absolute forward energy.

The plasma was preformed by irradiating a thin micro-disk of plastic with two 0.53 μm beams from each side, 2 ns before the interaction beam arrival. A third 0.53 μm beam was used to heat the plasma before the interaction. The initial foil thickness and laser energies were chosen in such a way that the foil had exploded a short time before the arrival of the interaction beams. The plasma was characterized by monitoring the spatial and temporal evolution of the $5/2\omega$ emission, generated by the 3ω probe beam scattering off the $\omega/2$ plasmon produced by the two plasmon decay of the interaction beam. This harmonic emission provides information on the position of the quarter-critical layer as a function of time. Two dimensional hydrodynamical simulations show the electron density on the target axis evolving from 0.45 to 0.2 n_c during the interaction pulse (n_c is the critical density for the 1.053 μm light). We observed similar timing and spatial location of the $5/2\omega$ emission with one or two beam irradiation, indicating that the electron plasma density was about the same in both cases. The electron temperature was measured using Thomson scattering from ISW fluctuations without any interaction beams, and was found to be 0.5 keV. Hydrodynamic simulations show some additional heating of the plasma up to 0.7 keV when one interaction beam is at full intensity.

Figure 1 shows time-resolved spectra of the transmitted light collected by the optics located along the direction of beam 1 as described above, when only beam 1 is present (left spectrum) and when both beams, 1 and 2, are present with equal average intensities (right spectrum). The latter spectrum is illustrated in more detail by three cross-sections at different times. The first cross-section shows a spectrum containing essentially an unshifted component of the transmitted light. After a transient period there is a sudden onset of a broad red shifted component as shown in cut 2. Cut 3 illustrates an equally broad spectrum at a later time. In both the cases 2 and 3 corresponding to times past the initial transient, the main part of the transmitted signal lies in the red shifted components. The experimental spectra in Fig. 1 display similarities between the single and crossed beam cases; however the crossed beam geometry strongly enhances the red shift component in comparison with the single beam results.

Next, we show in Fig. 2 the numerical spectra obtained from two dimensional simulations in which a system of nonparaxial electromagnetic and ion acoustic wave equations [11] was solved in Cartesian geometry. Our simulations extend previous crossed beam studies [12] to the case of two RPP beams. The two incident beams are symmetric with regard to the x-axis. The transmitted light is collected along different angles θ in the near-field domain and analysed spectrally. For comparison with the experimental data, we display in Figure 2 the overall transmitted light spectra obtained by summing up all the near field spectra corresponding to different directions of propagation within an angle of 180°. The electron temperature, T_e, and electron density, n_e, used in our numerical simulations were: T_e =0.5 keV, n_e =0.3n_c. The simulations were carried out over 300 ps, and they model the central part of the laser pulse duration in the experiments. The laser beam intensities were ramped in time, in order to account for the laser time history. The maximum average intensity of each RPP beam was I =5.4 $\times 10^{13}$ W/cm^2. As in Fig. 1 we compare the transmitted light spectra produced in a single beam interaction with that of the crossed beam case. The maximum laser intensity is reached in Figs. 1 and 2 at the moment corresponding approximately to the cuts 2. Initially, the main part of the spectrum lies in the unshifted component, as shown in the first cut. The cuts 2 in Figs. 2 and 3 illustrate the regime taking place just after the sudden onset of the red shifted component. In the simulations the onset of this red shifed component can be clearly identified as occuring at the moment when the average intensity of the beam speckles reaches the critical value for self-focusing. Thus, at this moment of time there is a large number of speckles which are unstable with respect to self-focusing and the subsequent instablities of a light trapped in a filament [13]. It is important to notice that it is approximately at the same moment of time that a broad red shifted component appears in the single beam spectra. The third cut in Fig. 2 corresponds to a broad spectrum, in which three distinct peaks can be seen, the total width extending up to 10 $\AA$ towards the red part of the spectrum.

Concerning first the single beam spectra, some differences can be seen between the simulations [Fig. 2] and the experiments [Fig. 1] results, the latter exhibiting a much broader red shift. As said before, this red shifted component is related to plasma induced beam smoothing. Our numerical modeling of the ISW nonlinearity (a simple logarithmic saturation of the density response) cannot properly account for the laser induced flow velocity contributing to the Doppler broadening of the ion waves which scatter the transmitted light. Moreover, we are modeling relatively small plasma (160 and 240 wavelengths in the longitudinal and transverse directions, respectively) with constant background conditions. Thus, our hot spot statistics of the interaction region is limited and may exclude significant nonlinear effects [13] due to very intense hot spots. In addition, our simulation results do not account for additional heating and hydrodynamical evolution. For all these reasons the temporal plasma induced smoothing of a single beam is not as efficient in the simulations as in the experiments.

We have found in simulations that whenever at least one of the interacting beams has a large red shifted component, it can act as a resonant seed for the large angle forward SBS of the unshifted part of the second beam. Such a forward SBS produces intense and broad red-shifted components of the first beam as seen in cuts 2 and 3 of Figs. 1 and 2. This interpretation is further supported by the following experimental results.

An increase by a factor 2.3 of the energy of the transmitted light collected by the optics located along the direction of beam 1 was measured when beam 2 was present. The analysis of the left spectrum of Fig. 1 shows that this increase is mainly due to the amplification of the red-shifted component of beam 1. For two incident beams of equal intensity this implies an increase of the overall transmission. Such an increase is partly due to reduced collisional absorption because of the higher temperatures obtained with crossed beam irradiation, and partly due to smaller backward SBS during the late stages of the interaction, as discussed further on. The enhancement of the red-shifted component as a function of the two beam characteristics has been studied experimentally as follows.

First, we have observed that the enhancement factor depends on the intensity of beam 2 : with beam 1 at its maximum intensity 8×10^{13} W/cm^2, this factor was 2.1 and 3.5 for beam 2 at 2.4×10^{13} W/cm^2 and 8×10^{13} W/cm^2, respectively. This increase is found to be associated with an increase of the overall intensity of the red-shifted component. The enhancement factor depends also on the intensity of beam 1. At low intensity of beam 1, the enhancement factor was larger than at high intensity: for beam 2 at its maximum intensity 8×10^{13} W/cm^2, this factor was 8 for beam 1 at 2×10^{13} W/cm^2 and 3.5 for beam 1 at 8×10^{13} W/cm^2, showing the saturation of the mechanism. These experimental features are confirmed by the simulations, in which the transfer of energy can be identified as taking place between the spectrally unshifted component of one beam and the red shifted part of the other. We also varied in our simulations the relative intensities between the beams. We observed that the transfer of energy between the beams mediated by the mechanism described above results in the equilibration of their energy fluxes.

Using complementary masks on the transmitted light diagnostic, we have observed that the presence of the second beam increases the energy which is scattered outside the solid angle of beam 1, and that the red-shifted component is mainly due to the light coming outside this beam cone. The simulations reproduce very clearly this experimental observation, supporting our interpretation. The near field spectra in the case of a single beam interaction show indeed that the spectral broadening associated with a plasma induced smoothing is important for directions corresponding to a transmission ouside the incident cone only. Thus the forward SBS of the unshifed part of beam 2 can be seeded only by these red shifted components of beam 1 which propagate outside the incident cone of beam 1. For this reason, the near field diagnostics in the case of two beam illumination shows that the transfer of energy between the beams involves forward SBS at approximately 30°, which would lead to a frequency shift of $\approx 3\AA$ according to the linear matching conditions for forward SBS. This linear estimate is of the same order in magnitude as the observed red shifts. The difference can be attributed to the intricate interplay between the plasma induced smoothing effects on each of the interaction beams and the large angle forward SBS taking place between them. The fact that the two beam experiments results are very well reproduced by the the corresponding simulations represents an additional argument in favor of our interpretation, i.e. the red shifted component of a single beam spectrum appears indeed to be sufficiently broad to act as an efficient seed for large angle SBS, in spite of weaker plasma induced smoothing effects in the one beam simulations than in the experiments.

The Fourier spectra of density fluctuations shown in Fig. 3a correspond to the time associated with cuts 1 of Figs 1 and 2. For small values of k_x, they display the three distinct components corresponding to the stationary density perturbations produced by the optical mixing of two top hat RPP beams [8]. The temporal ramping of the laser intensity has eliminated the initial transient effects [14] of the ISW excitation which would be generated by an instantaneous turn on of the laser ponderomotive force in simulations. The transmitted light has already been broadened in angle but no additional frequency components are observed at that time in the frequency spectrum (cf. Figs 1 and 2). The components of the ion wave spectrum in Fig. 3a at $k_x \approx 2k_0$ are associated to backward

SBS along the directions of each beam, and to the stimulated scattering of one beam into the backward direction of the other - the so called symmetric mode ($k_y = 0$) [15] which has been identified before by Thomson scattering in Ref. [1]. At the later time corresponding to the cuts 3 in Figs 1 and 2, Figure 3b shows that the three small k_x-components are now significantly broadened in comparison with that of Figure 3a. This broadening is the result of plasma self-induced smoothing effects for the two spectral components corresponding to the optical mixing of the interacting RPP beams, and of large angle forward SBS for the central part of the small k_x-spectrum. At the same time the backward SBS driven fluctuations are dramatically reduced. Such an effect has been observed experimentally before [1]. We interpret it as resulting from the enhancement of the bandwith and angular spread of the forward propagating light, leading to a reduction of the backward SBS gain coefficient [21]. Suppression of backward SBS was explained in Ref. [16] as due to the ISW nonlinearity. The latter mechanism is likely to be more important for plasma densities lower than the one considered here, as plasma self-induced beam smoothing is less effective for low plasma density.

In conclusion, we have reported on the first spectral analysis of the transmitted light for equal intensity crossed beam interactions, showing broad red shifted spectra and angular spreading. The large angle forward SBS between the beams directions is triggered by single beam plasma induced smoothing effects. In addition to enhancing the spectral width and angular spreading, this large angle forward SBS is able to contribute to the energy exchange between the beams. The crossed beam geometry irradiation makes also plasma induced smoothing more efficient in reducing the backward SBS reflectivity.

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* Present address : Department of Physics, University of Nevada, Reno, USA

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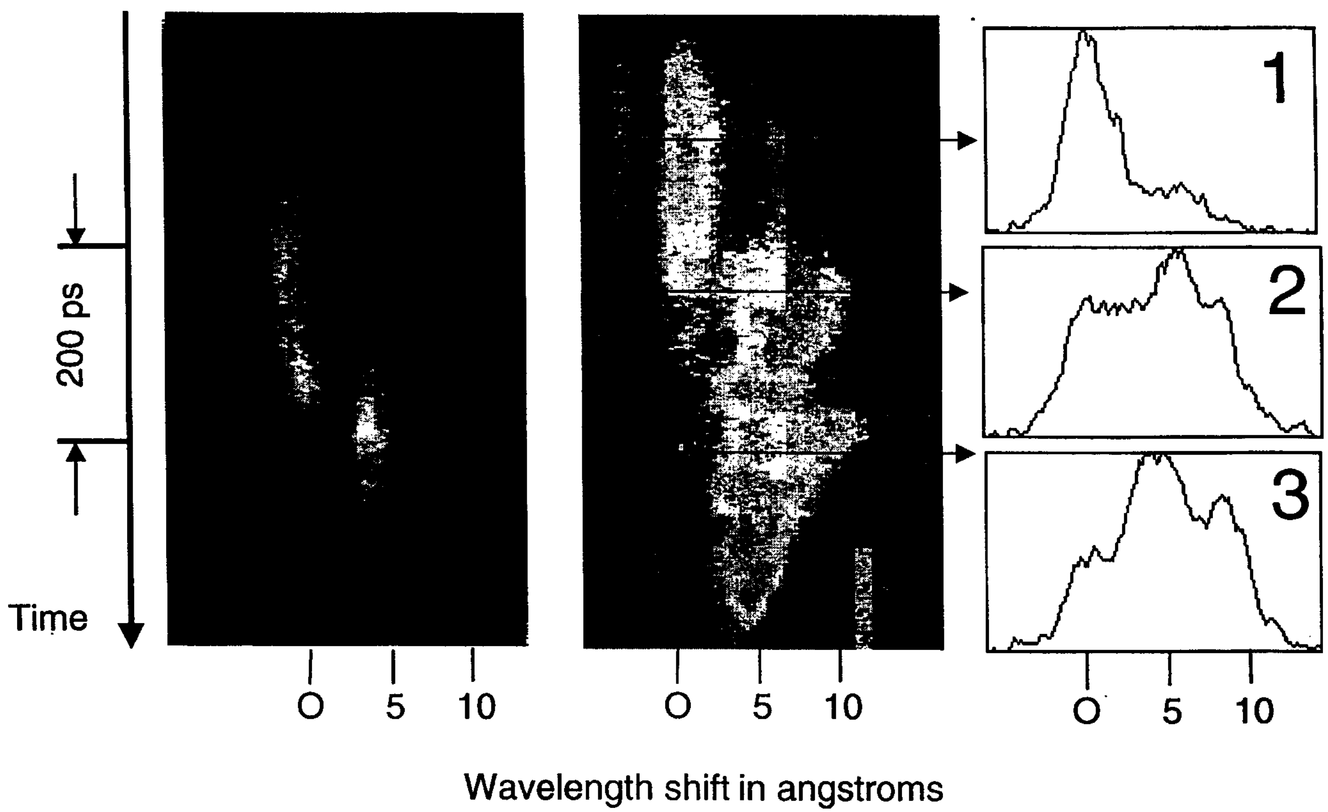
FIGURES

FIG. 1. Time-resolved spectra of the transmitted light collected in the experiment by the optics located along the direction of beam 1, when only beam 1 is present (left spectrum) and when both beams, 1 and 2, are present with equal average intensities (right spectrum).

FIG. 2. Frequency spectra of the transmitted light obtained from two dimensional simulations for T_e =0.5 keV and n_e =0.3n_c. A single beam interaction corresponds to the left spectrum. The two equal intensity crossed beams produce the right spectrum.

FIG. 3. Density fluctuation spectra at early time (a) (corresponding to the moment of time of cuts 1 in Figs. 1 and 2). (b) corresponds to the late time moment.



200 ps
Time
1
2
3
O
5
10
O
5
10
O
5
10
Wavelength shift in angstroms

Figure 1

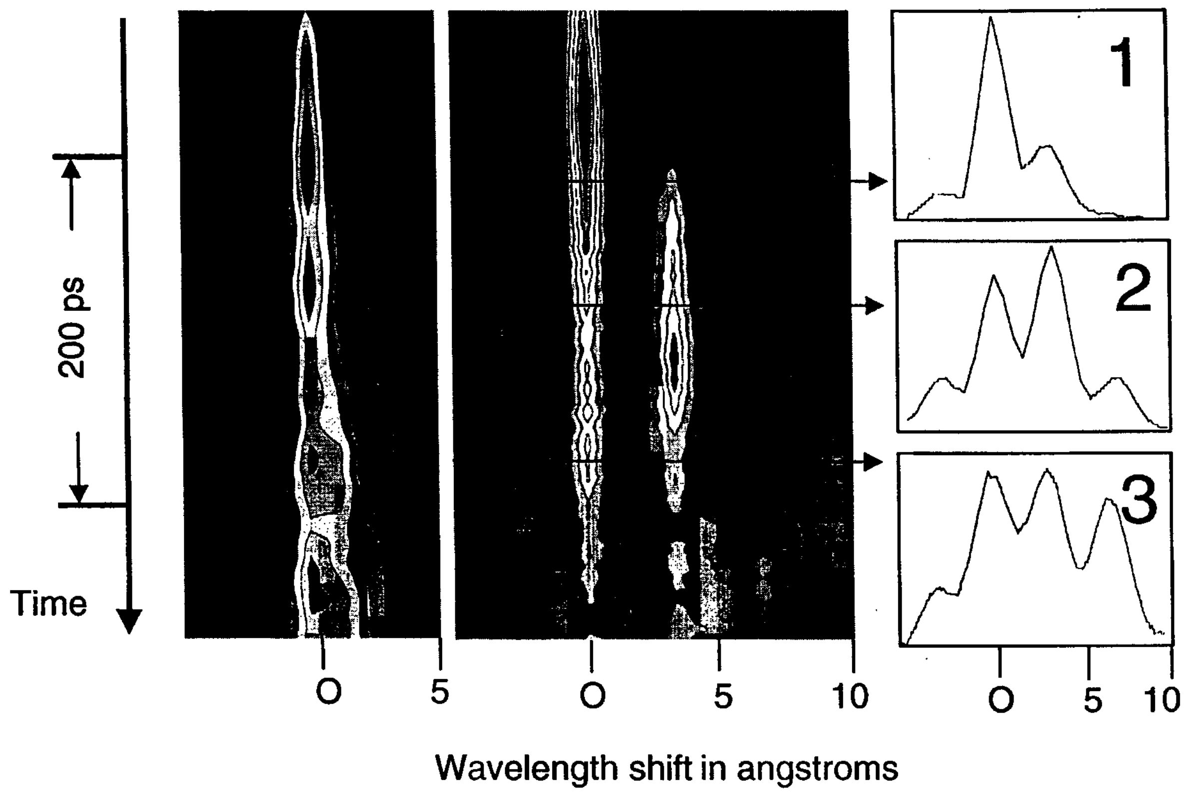


Figure 2

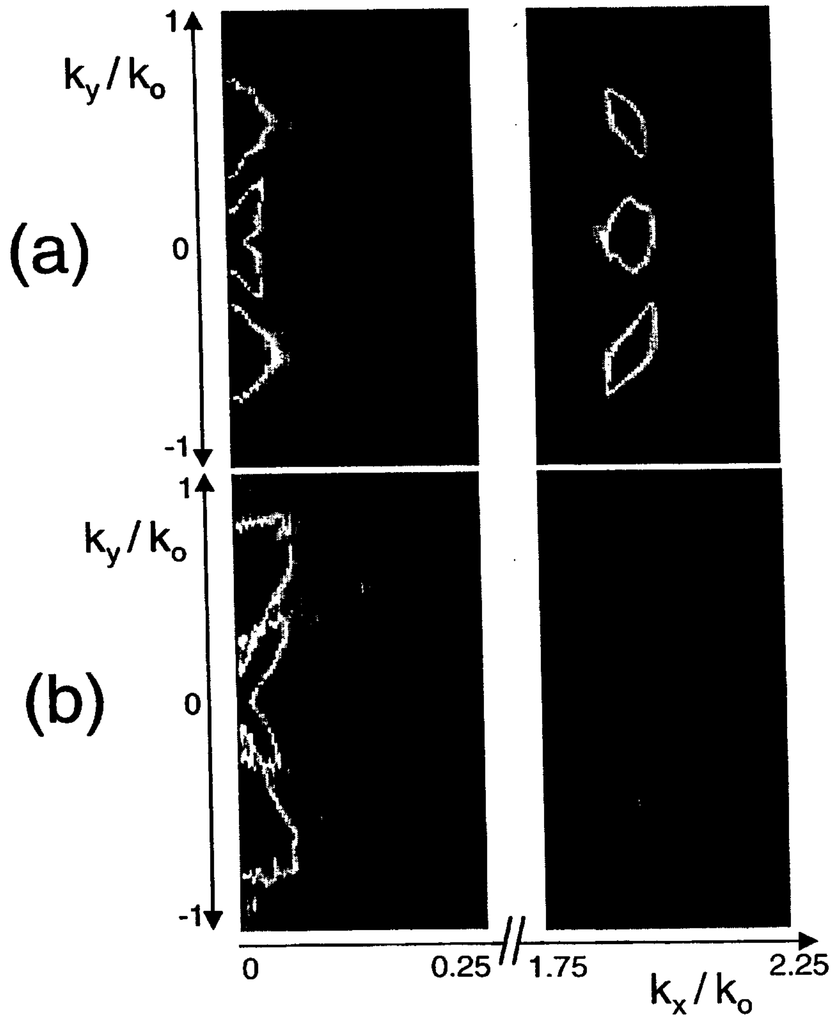


Figure 3